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# INTEGRATING CHEMICAL ENGINEERING FUNDAMENTALS IN THE CAPSTONE PROCESS DESIGN PROJECT

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## ABSTRACT

All B.Eng. courses offered at the Technical University of Denmark (DTU) must now follow CDIO standards. The final “capstone” course in the B.Eng. education is Process Design, which for many years has been typical of chemical engineering curricula worldwide. The course at DTU typically has about 30 students. The B.Eng. education lasts for 3½ years (seven semesters), of which the 5th semester consists of practical training with a company and the final (7th) semester consists of a research project. The design course falls in the 6th semester, and is thus the last formal instruction that the students receive. The education is designed to provide students with the necessary tools to become productive in a company in a short time – so there is a strong industrial focus. Some students choose to continue with their studies and can then complete an M.Sc. after a further two years of study.

The demands of the CDIO standards – especially standard 3 – Integrated Curriculum - means that the course projects must draw on competences provided in other subjects which the students are taking in parallel with Process Design – specifically Process Control and Reaction Engineering. In each semester of the B.Eng. education, one course is designated the “project” course, which should draw on material learned in parallel courses. In the 6th semester, Process Design is the project course. Process Control and Reaction Engineering are then incorporated into the final plant design project. Specifically, almost all chemical plants will incorporate one or more chemical reactors. In the initial stages of a process design, it is sufficient to express simply the reactor inputs and outputs. However in later stages, details about the reactor need to be specified. This is only possible using tools learned in the course Reaction Engineering. In order to incorporate reactor design into process design in a meaningful way, the teachers of the respective courses need to collaborate (Standard 9 – Enhancement of Faculty CDIO skills). The students also see that different components of the chemical engineering curriculum relate to each other. Similarly, in process design, steady state is always assumed for processes (i.e. production of a given chemical occurs at a constant rate, temperature, pressure and composition; feeds enter the plant at constant rates, etc.). However, in practice, chemical plants need to be carefully controlled to operate at a specified set of steady-state conditions. This is the science of Process Control and the students are asked to apply what they have learned here in order to show how to control the operation of the plant they have designed.

The key difference from typical (earlier) process design courses is that the interaction between the courses is formalized, requiring (amongst other things) increased, broader teacher competence and communication between teachers across different disciplines, thereby also tying in with Standard 9 – Enhancement of Faculty CDIO skills.

From a CDIO perspective, Process Design provides an opportunity for a comprehensive implementation of CDIO principles in a single course. Already the traditional chemical engineering “capstone” design course has for decades embodied many of the essential features of CDIO (for example the focus on group work, development of interpersonal skills, the open-ended nature of design problems, etc.).

**KEYWORDS**

Process Design, Integrated Curriculum, Capstone Project, Enhancement of Faculty CDIO skills.

## INTRODUCTION AND BACKGROUND

The Technical University of Denmark (DTU) educates engineers in two separate streams of education, one stream being the Bachelor of Engineering (B.Eng.) which is a 3½ year program that qualifies the student to go directly into industry [1]. DTU’s management decided to introduce CDIO as the engineering context for all its B.Eng. studies, and implementation started in 2008 with first year courses. In 2011 the process will be complete.

In the Department of Chemical and Biochemical Engineering, the 3½ years (7 semesters) are arranged such that the 5$^{th}$ semester is where the students undergo practical engineering training in a company, and the 7$^{th}$ semester is devoted to the final research project. Large design/build projects are undertaken in the 1$^{st}$ and 4$^{th}$ semester [1].

Process Design (course number 28157) is given in the 6$^{th}$ semester, sandwiched between practical training and the final project. It is a 5 ECTS points course given simultaneously with Process Control (5 ECTS points) and Reaction Engineering (5 ECTS points). These courses thus offer the last opportunity for instructional education before the students begin working. Furthermore, the Process Design course is designated as the “project course” for the semester, which means that the final course evaluation is based mainly on project work which must also include elements from the courses Process Control and Reaction Engineering. If the students have taken and passed all the preceding courses in the B.Eng. curriculum then these three courses are the only ones they take in the 6$^{th}$ semester.

After completion of the B.Eng. curriculum, some students choose to continue their education with an M.Sc. in Engineering, which they may do after undertaking certain “bridging” courses. In this case they are required to take the course Process Design: Principles and Methods (28350, 10 ECTS points). This is a more advanced (and more intensive) course than 28157. Students will also encounter more advanced courses in Process Control and Reaction Engineering if they choose to continue to the M.Sc.

## STRUCTURE AND CONTENT OF THE COURSES

### *Process Design*

The course is run over 13 weeks. Since it is a 5 ECTS point course, 1 module is assigned to the course per week. The course runs from 8 am to 12 pm every Wednesday. This is the case for all DTU courses (a four-hour period is assigned – either 8 to 12 or 13 to 17 for each 5 ECTS point course). Teachers have freedom as to how they utilize this time, but it is usually divided between short lectures, in-class problem-solving sessions, group exercises and project work. Extensive use is made of the “Databar” – a classroom where the teacher and each student have a computer in front of them. Problems and projects which require use of software are carried out here. The students can be guided through an exercise since the teacher's actions are projected onto a screen. There are typically 25-35 students in the course.

There is no final written exam – the course consists of three projects (P1 – P3). The first and third projects (P1 and P3) are performed in groups of 4-5 and the second project (P2) is performed individually. Project P2 follows on from P1 and P3 from P2. For example, the students have had to design a plant that produces 100 000 tons per year of cumene. In project P1 the overall process flowsheet is defined and the students identify that the key unit operations are a reactor, several heating and cooling units, and distillation columns for separation of the various products and reactants. Based on this (approved) flowsheet the students divide the individual units among themselves and then do a detailed design of these units individually. Project P3 then brings the whole process together again and the students perform an economic, environmental and process control analysis of the process in their groups. Most of the grade is assigned to the project work, but about 10% depends on a short individual oral examination.

Process design follows the text by Duncan and Reimer [2]. The students are introduced to the design process by way of examples from very different types of processes. These include processes for the production of ammonia, the purification of heptane, production of electronics grade silicon, generation of electricity from fuel cells, desulfurization of natural gas, desalination of seawater, refrigeration. The emphasis is on the features common to these processes. Detailed design of certain common unit operations is covered (distillation columns, heat exchangers). Economic and environmental aspects of process design are also covered, while reactor design is covered in the Reaction Engineering course which runs concurrently. Similarly process control aspects of the course are left to the Process Control which also runs concurrently.

For the projects, the students have (up until now) been given a specific bulk chemical (cumene) and told that they need to design a process to make 100 000 tons of it per year. There are three projects in process design – the first and third are solved in groups and the second individually. However each project depends on the one before it, so collaboration (or at least communication) is required even in the individual design. During the course extensive use is made of the commercial design program PRO/II [3].

Figure 1 shows a flowsheet for a typical large scale plant for bulk chemical production – in this case cumene. Cumene is produced in a continuous process using benzene and propylene as feeds. In this case the propylene contains 5% propane as an impurity. The propane does not react in the reactor. On addition to the desired product (cumene) and unwanted side product (di-isopropyl benzene, PDIPB) is also produced. In the reactor. Since the reaction is not 100% complete in the reactor, unreacted benzene and propylene is separated in a distillation column and recycled to the beginning of the process. The unwanted product PDIPB is also separated from cumene in a second column.

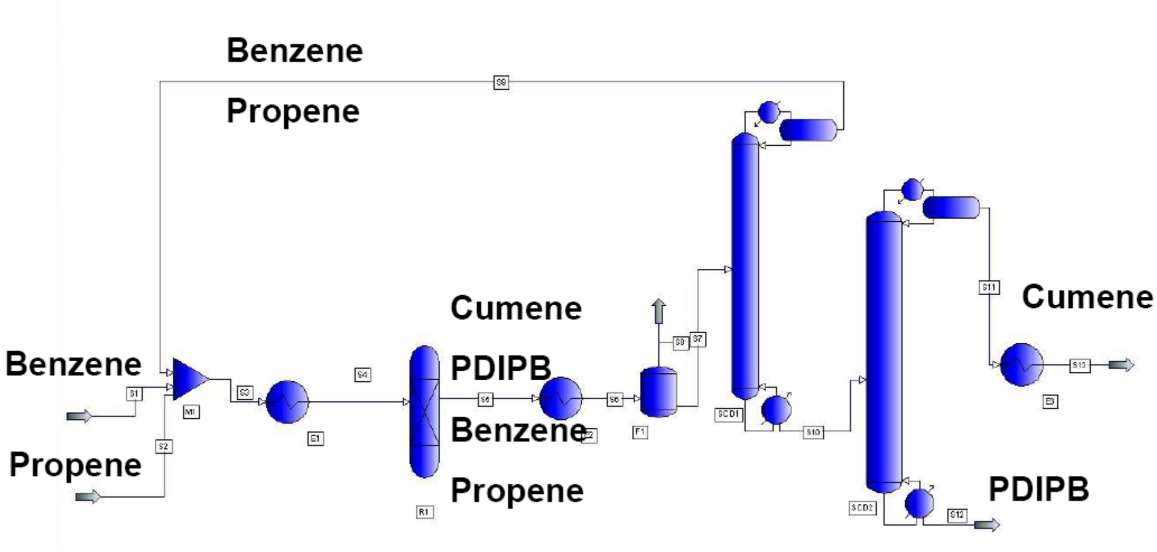


Figure 1. Simplified flowsheet of a 100 000 ton/year plant for the continuous production of cumene from propylene and benzene. Only the major unit operations are shown (heat exchange, reaction, distillation).

### ***Process Control***

Most of the chemical engineering curriculum concerns processes operating at steady state, such as the one shown in figure 1. The concept of steady-state is itself a little hard to grasp for students fresh from high school, since it is quite foreign to the chemical processes we are exposed to in daily life, such as cooking, or doing laundry. These are batch processes: ingredients (raw food, dirty laundry, washing powder) go in, we wait while the reaction proceeds in the reactor (oven, washing machine) and then take out the products (ready food, clean clothes). Even school laboratory experiments are usually batch processes. But the vast majority of chemical processes are steady state processes – for example in figure 1 there is (ideally) a constant flow, 24 hours a day, with fixed temperature, pressure and composition in all the streams shown.

But plants are put into operation, are shut down, are subjected to differing operating conditions and disturbances. Process control addresses these situations. The course aims at an understanding of how process dynamics and process control is related, and of the construction and significance of control systems. This includes the underlying theory and certain components employed. The course emphasizes the application and setting of standard controllers used in simple feedback control and other enhanced control strategies. Also, students should be enabled to plan instrumentation of simple plants.

In the context of the Process Design course, it would be too much for students to design a control strategy for the entire plant. Rather, they are asked to comment qualitatively about how to control a distillation column – a notoriously complex control problem on a plant, about which whole books have been written. Figure 2 shows a schematic of a distillation column where the 5 control valves which can be manipulated are highlighted. Controlling these in a judicious manner ensures the correct (design) flowrates of products as well as the correct purity in these product streams.

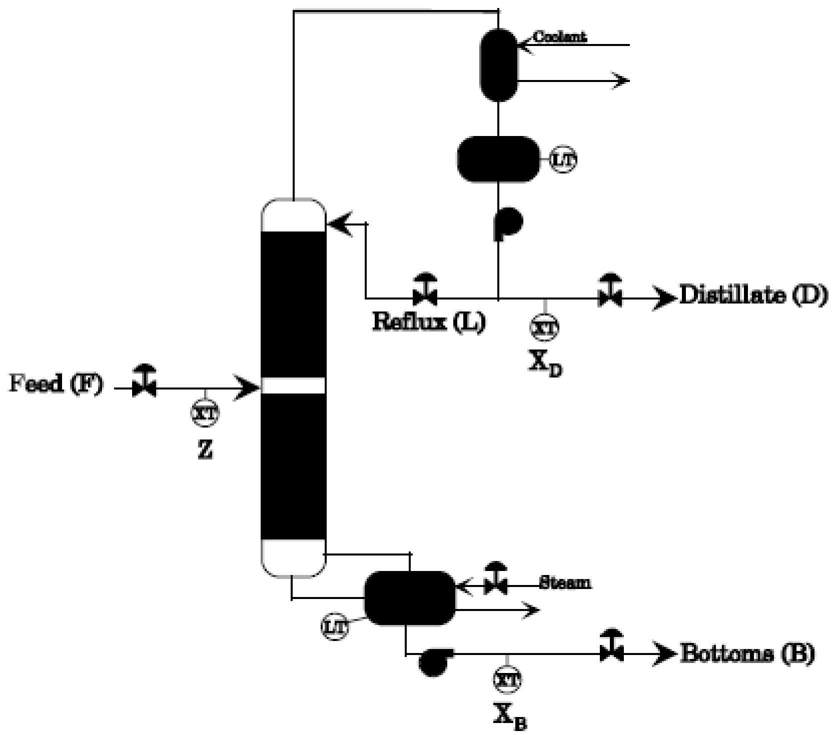

Figure 2. Schematic of a distillation column, showing the five flow control valves that can be manipulated to achieve the desired product flowrates and purity [4].

***Reaction Engineering***

The aim of this course is to give the students a basic knowledge of the connection between chemical kinetics and reactor design so that they will be able to demonstrate the methods of calculation and solutions to chemical reaction engineering problems; to teach the planning of laboratory experiments, the treatment of data and the calculation of main dimensions of simple reactors for homogeneous, heterogeneous and bio-tech reactions; to provide knowledge of the most important reactor types, their use and design.

In the context of the Process Design course, reaction engineering knowledge is required to design the reactor shown in the flowsheet in figure 1. The reactor is filled with catalyst which enables the reaction to occur in the desired direction. Students are given limited information about this process and will need to interact with the Reaction Engineering teacher to solve this problem. Since the detailed reactor design is part of project P2 – the individual unit operation design, about one quarter of the students will have to undertake this design. An engineering drawing showing the complexity of a such a reactor (fixed catalyst bed) is shown in figure 3.

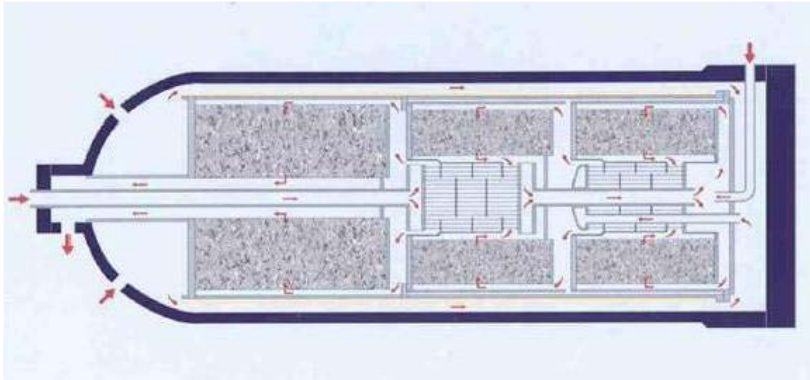

Figure 3. A fixed bed reactor for the production of ammonia (courtesy Haldor-Topsøe).

## THE COURSES IN THE CONTEXT OF CDIO AND CDIO STANDARDS

As with all courses at DTU, the course syllabi are defined in terms of learning outcomes (standard 2 – CDIO syllabus outcomes). In the final semester there is a *prescribed* integration of the curriculum across the semester (standard 3). This in turn activates faculty to collaborate across course boundaries and lessens the isolation that often occurs in teaching. Personal and interpersonal skills are integrated into the course in terms of teambuilding (most of the project work is done in groups) – standard 7 – integrated learning experience. The course also requires expertise in several prerequisite courses, so it is really where students see how *everything* they have learned comes together. Design courses almost by their nature require active learning (standard 8), but by having syllabus follow CDIO guidelines, the relevance of design and the importance of its role in engineering education is emphasized in a natural way. Again the collaboration of faculty across the board, requires not only disciplinary skill development amongst faculty, but CDIO skill development as well (standard 9). Again this follows naturally once CDIO is written into the fabric of a course and a curriculum.

## THE STUDENT EXPERIENCE SO FAR

Generally students have been happy with the course (based on very data so far), although there was occasionally a sense of frustration that a single teacher could not help with all problems/questions.

Elements that students liked included the interactive way the course is taught; The use of real-life software tools; The teaching method of lectures broken with problem-solving sessions; Working in groups; Focus on project work. All of these should bring a smile to a CDIO believer's face.

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## *Biographical Information*

Nicolas von Solms is an associate professor in the Department of Chemical and Biochemical Engineering, Technical University of Denmark. His background is in thermodynamics – modelling and measurement of phase equilibrium properties, mostly in complex mixtures (oil, polymers, gas hydrates, hydrogen-bonding fluids). He teaches Process Design to final-year B.Eng. students.

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Jens Abildskov is associate professor at the Department of Chemical and Biochemical Engineering, Technical University of Denmark. His background is in modeling of separation processes and thermodynamics – modelling of phase equilibria and simulation of thermodynamic properties of fluids and fluid mixtures. He teaches Process Dynamics and Control to final-year B.Eng. students.

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